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Integration of energy storage with hybrid solar power plants

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Abstract

Concentrated solar power (CSP) and photovoltaics (PV) systems integrated with energy storage have large potential to provide cost-competitive and baseload renewable energy. On the one hand, CSP with thermal energy storage (TES) is an affordable and dispatchable option. On the other hand, Electrical Energy Storage (EES) gives dispatchability to PV systems but at high costs due to current prices of EES systems, however an extreme reduction in EES costs is expected. Therefore, there could be a tipping point at which PV + EES becomes the best technology to provide dispatchable power. Here, we explore different scenarios, representing snapshots of technology investment costs according to published projections, in order to identify the dominant technology in a hybrid solar power plant that provides sustainable and dispatchable energy by 2050. The study uses our two-stage multi-objective optimisation framework, in order to optimise the design and operation of a hybrid power plant with energy storage. We found that nowadays CSP with TES is the most affordable technology, but a shift to PV with EES is expected mainly due to the large reduction in the cost of both PV and EES systems. Thus, the presented optimisation analysis can improve the strategies for the design of an effective and economic pathway to decarbonise the power sector.

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Keywords: Thermal and electrical energy storage; hybrid energy system; dispatchability.

1. Introduction

The large fluctuations of electricity supplied from the intermittent resource in renewable power plants can be reduced by the integration of energy storage. For large scale solar power plants, suitable forms to store energy are electrical energy storage (EES), which is appropriate to store the electrical energy coming from a photovoltaic (PV) power plant, and thermal energy storage (TES), beneficial for solar thermal or concentrating solar power (CSP) plants.

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PV systems are one of the more affordable technologies to provide electricity and are expected to be the cheapest form in the near future [1]. In Chile, the levelised cost of energy (LCOE) of a PV plant without storage is around 90 USD MWh^{-1}, while it is close to 130 USD MWh^{-1} for a CSP plant with 17.5 h of TES and a solar multiple of 2.6 (the design capacity of the solar field respect to the capacity of the power block) [2]. In terms of the storage system, investment costs of TES are in the order of 25 USD kWh^{-1} (thermal), and EES system costs are around 600 USD kWh^{-1} (electrical energy, DC) [3]. Then, if we include the efficiencies to transform both thermal and DC to electrical AC, TES systems are around 10 times cheaper than EES. Thus, CSP systems integrated with TES are currently one of the most cost-competitive technologies to provide reliable and baseload power and it becomes more affordable when hybridised with PV [2]. However, in the medium-term, EES systems are expected to have an extreme reduction, and then PV with EES could be the best option.

According to published projections, cost reductions depend on the learning rate of each technology. In the case of PV and battery systems, [1] analyses the projections of costs for the modules, inverter and balance of system as well as the improvement in efficiencies, and concluded that the total investment cost of a PV system will decrease between 40% and 70% by 2050. Another study [4] reported that the expected reduction in PV costs without tracking could be in the range of 50% to 60%. Regarding utility scale EES systems, some publications estimate that their costs could be closer to 100 USD kWh^{-1} by 2050 [5, 6]. Otherwise, expected reduction for CSP and TES systems are in the range of 20% to 30% [4, 7]. Finally, a reduction between 20% and 40% in operational and maintenance costs (O&M) for both technologies are considered in this study.

In this paper, these estimations are used to definite different scenarios of cost reduction, based on 2016 costs, where each scenario represents a particular level of learning rate reached for each technology by 2050. These levels will be interpreted as investment and O&M costs and used as parameters in a two-stage multi-objective optimisation framework [2]. Finally, the results of each scenario will be analysed to find the features of the dominant technology in a hybrid solar power plant that provides sustainable and dispatchable energy.

2. Methods

2.1. Optimisation Framework

The method used in this study, detailed in [2], optimises the design of a hybrid power plant by a multi-objective genetic algorithm. Then, as a nested process, the operation is optimised by a multi-objective automated linear programming routine. In order to exploit synergies of hybrid power plants that integrates two different renewable technologies and two types of energy storage, the objectives of both, the design and operational stages, have to be linked [2]. This method focuses on improving both financial and technical performance with the aim of increasing competitiveness of solar energy. The present study focuses on an affordable and dispatchable power, hence, the objectives in the two stages are:

1. Multi-objective design optimisation: Min{LCOE}, Min{Investment}, Min{LPSP}
2. Multi-objective operational optimisation: Max{E^{Supply}}, Min{LPSP}

LPSP is the loss of power supply probability, and ESupply is the total amount of energy supplied by the power plant during one year of operation. The LCOE is given by [8]:

$$LCOE = \frac{TLCC}{E^{Supply}} \cdot \frac{r}{\left(1-\left(1+r\right)^{-N}\right)} \tag{1}$$

where TLCC is the total life cycle cost. This study uses an annual interest rate r = 7%, and a lifetime N = 25 years.

To quantify the dispatchability, the loss of power supply (LPS_i) accounts the power shortage (in MW) when demand exceeds supply, and the loss of power supply probability (LPSP) is defined as the fraction between the sum of these shortages and the total energy commitment during one year:

$$LPS_i = \begin{cases} P_i^{Commitment} - P_i^{Supply}, & P_i^{Supply} < P_i^{Commitment} \\ 0 & , P_i^{Supply} \geq P_i^{Commitment} \end{cases} \tag{2}$$

$$LPSP = \sum_{i=0}^{T} \left(LPS_i \cdot \Delta t_i \right) \Big/ \sum_{i=0}^{T} \left(P_i^{Commitment} \cdot \Delta t_i \right) \tag{3}$$

where $P_i^{Commitment}$ is the demand that needs to be met and P_i^{Supply} is the actual power supplied in period i.

2.2. Case Study

As a case study, the design of an off -grid power plant that delivers energy to Spence, a copper mine in the Atacama Desert in Northern Chile (Southern hemisphere), is modelled. Hourly power demand was obtained from [9] and solar irradiation information for the typical meteorological year from [10]. Technical and financial performance of CSP and PV power plants, i.e. efficiencies, capacities, investment costs, operational and maintenance cost are estimated by using SAM-NREL [3]. Figure 1 shows the hourly power demand for Spence, the direct normal irradiation (DNI) and the global solar irradiation (GHI) during one week in summer (January) and one week in winter (July) 2016. The diagram reflects, among others, the shape of the demand profile required to be met, and the mismatch between demand and solar resource availability. Spence maximum power demand for 2016 was 83 MW, its average power consumption was 58 MW, and the reported solar irradiation for that year was: DNI ≈ 3,500 kWh m^{-2}, GHI ≈ 2,630 kWh m^{-2}.

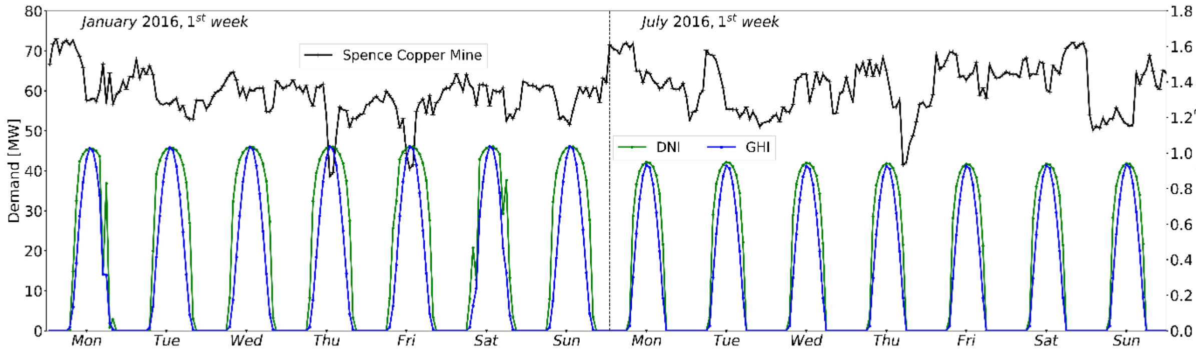

Fig. 1. Spence copper mine electricity demand and solar resource in Northern Chile.

3. Results and Discussion

Table 1 shows the five scenarios considered, based on 2016 costs and combining different levels of reductions by 2050 between CSP + TES and PV + EES technologies. As an example, Scenario 1 (S_1: $L_{r\,CSP}$, $L_{r\,PV}$) considers a low reduction in CSP technology costs ($L_{r\,CSP}$), i.e. 20% reduction in both investment and O&M costs, and a low reduction in PV system costs ($L_{r\,PV}$), i.e. 40% reduction in investment cost for PV, 60% decrease in investment cost for the EES system, and 20% reduction in O&M costs for the PV+EES power plant.

Table 1. Scenarios defined though different cost reductions

Scenario		Investment $_{(CSP+TES)}$	Investment $_{(PV)}$	Investment $_{(EES)}$	O&M cost $_{(CSP+TES)}$	O&M cost $_{(PV+EES)}$
S1	$L_{r\,CSP}$, $L_{r\,PV}$	20 %	40 %	60 %	20 %	20 %
S2	$L_{r\,CSP}$, $H_{r\,PV}$	20 %	60 %	80 %	20 %	40 %
S3	$M_{r\,CSP}$, $M_{r\,PV}$	30 %	50 %	70 %	30 %	30 %
S4	$H_{r\,CSP}$, $L_{r\,PV}$	40 %	40 %	60 %	40 %	20 %
S5	$H_{r\,CSP}$, $H_{r\,PV}$	40 %	60 %	80 %	40 %	40 %

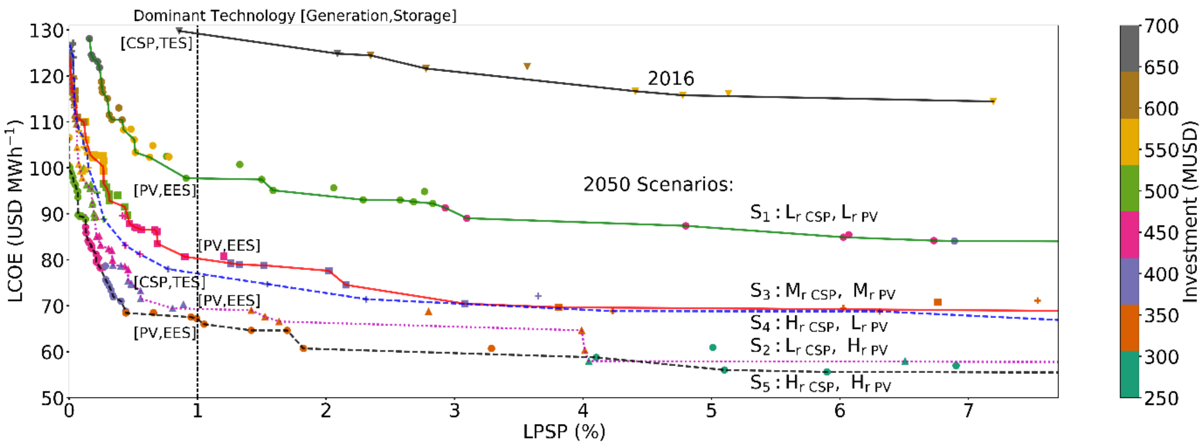

Fig. 2. Multi-objective Pareto optimal solutions: Min{LPSP}, Min{LCOE}, Min{Investment}

The two-stage multi-objective optimisation framework was implemented for each scenario. For each scenario, the results create a three dimensional Pareto optimal surface summarising the three objectives chosen in the design optimisation stage, highlighting current and future configurations of hybrid power plants to provide affordable and reliable energy from solar technologies. From all solutions, just those that meet the following requirements are displayed in Figure 2: LPSP ≤ 8%; LCOE ≤ 130 USD MWh^{-1}; investment cost ≤ 700 MUSD. Each point represents a design of a hybrid solar power plant and the lines, to facilitate the reading, show the two-dimensional Pareto front considering LCOE and LPSP.

Figure 2 reveals that for all scenarios, a substantial reduction in LCOE and investment costs are expected. For instance, for a current design, a LPSP ≈ 1% (follow the vertical line in LPSP = 1%) is reached with a LCOE close to 130 USD MWh^{-1}, and a budget close to 700 MUSD. In the case of the most conservative scenario (S_1) the same level of dispatchability is achieve with a LCOE ≈ 100 USD MWh^{-1} and an investment near 500 MUSD. On the other hand, a power plant designed under the most optimistic scenario (S_5) attains a LPSP ≈ 1% with a LCOE of around 65 USD MWh^{-1} and an investment around 350 MUSD.

It is interesting to note that in terms of the dominant technology, CSP with TES is currently the best option for an affordable and dispatchable solar hybrid power plant. This trend will continue just in scenario 4 (S4: $H_{r\,CSP}$, $L_{r\,PV}$) that considers a high reduction in CSP+TES and a low reduction in PV+EES system costs. In all other cases, a shift to PV with EES as a dominant technology is expected.

Figure 3 shows the optimal design of the power plant with LPSP ≈ 1% for each scenario (including 2016). This diagram exhibits the normalised value of the three objectives considered in the design optimisation, and then three features of the design for optimised power plants are expanded, these are defined by: (i) A_{SF}, the fraction between the solar field area (m^2) of the CSP power plant and the total solar field area (CSP+PV); (ii) $E_{STO,Max}$: the maximum capacity based on electrical energy (MWh_e) of the thermal energy storage as a percentage of the total energy storage capacity (TES+EES); (iii) $E^{Supply,e}$: the electricity supplied by the CSP plant divided by the total energy supplied from the hybrid power plant. Hence, the design of hybrid solar power plants for scenarios 2016 and S_4 are dominated by CSP+TES. For all other scenarios (S_5, S_1, S_3 and S_2) their designs are dominated by a great PV solar field area, a similar or larger capacity for the EES system compared with the TES, and finally, the PV system supplies more than 80% of the total energy dispatched.

As expected, these values satisfactorily support the idea that in the medium term, the integration of photovoltaic and EES systems will be the most cost-competitive technology to provide dispatchable energy. The optimisation framework can be extended to incorporate other strategies or technologies, for instance demand side management, heat demand analysis, fossil backup, among others, which could improve both technical and financial performance.

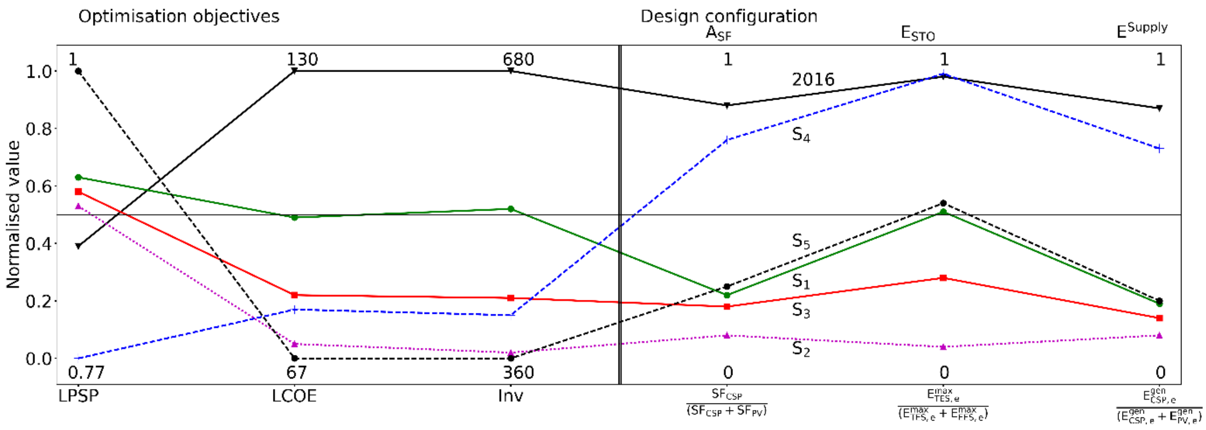

Fig. 3. Hybrid solar power plants designs with LPSP ≈ 1% for each scenario.

4. Conclusion

This study outlines a valuable approach to design optimised hybrid solar power plants under different objectives and assumptions. Our findings confirm that currently, CSP with TES is the most competitive technology to provide affordable and reliable energy, but a shift to PV with EES is expected mainly due to the extreme reduction in the cost of EES systems. Furthermore, in all future scenarios, a considerable improvement in financial performance of solar hybrid power plants is expected. This method represent a valuable blueprint for current and future researches in order to have a wider range of cost-competitive, reliable and sustainable technologies. This procedure can be extended to investigate diverse configurations in order to combine different energy generation and energy storage technologies as a single technology as well as hybrid power plants. Moreover, to design an effective and economic pathway to decarbonise gradually the power sector, the model could analyse the construction of PV plants in the short term and the integration of EES in the medium term. The study of objectives related not only to financial and technical parameters but also societal or environmental indicators can be useful to improve the strategies of decision and policy making. Finally, the analysis of the uncertainties would be favorable to improve the quality of the results.

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